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Chemical Enrichment and Energetics of the ICM with Redshift

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Abstract. In this paper we show preliminary results concerning the chemical and energetic enrichment of the ICM by means of supernova-driven wind models in elliptical galaxies. These models are obtained by taking into account new prescriptions about supernova remnant evolution in the interstellar medium. We find that models, which can reproduce the Fe abundance and the $[\alpha/\text{Fe}]$ ratios observed in the ICM, predict that the SN energy input can provide about 0.3 keV per ICM particle. We have obtained this result by assuming that each SN explosion inject on the average into the ISM no more than 20% of its initial blast wave energy. The predicted energy per particle is not enough to break the cluster self-similarity but is more than predicted in previous models.

1. Introduction

Hydrodynamical simulations and semi-analytical models for clusters of galaxies need an extra-energy of about 1 keV per ICM particle (e.g. Wu et al. 2000; Bower et al. 2000; Bialek et al. 2000; Borgani et al. 2001) to be reconciled with X-ray observations. In this framework one of the open problems is to assess whether SNe can provide this energy in order to break the cluster self-similarity (e.g. Finoguenov et al. 2001) or not (e.g. Valageas & Silk 1999; Bower et al. 2000). On the other hand, as shown by Matteucci (this conference), several successful models for the chemical enrichment of the ICM have been developed in last twenty years. We remind that a good model for the ICM chemical enrichment must produce $(Fe/H)/(Fe/H)_{\odot} \sim 0.3$ (e.g. White 2000) and $[\alpha/Fe] \sim 0$

(e.g. Ishimaru & Arimoto 1997; Renzini 2000). Since the galactic ejecta carry out energy with them we adopted the approach by Matteucci & Vettolani (1988) for computing the wind energy in models which match the observational constraints on the chemistry of the ICM. We modified the chemical evolution codes developed by Matteucci & Gibson (1995) and Martinelli et al. (2000) including a new cooling time for supernova remnants (SNR) depending on metallicity (Cioffi & Shull 1991) as well as new prescriptions for SNIa cooling (Recchi et al. 2001, section 2). Then we followed the evolution of the ICM abundances with redshift (section 3). In section 4 some results are shown and some conclusions are drawn.

2. Chemical Evolution Model

Chemical evolution models (both one and multizone) are those of Matteucci & Gibson (1995) and Martinelli et al. (1998). We focus here on the new energetic prescriptions implemented in the chemical evolution code. We follow the SNR evolution in the interstellar medium according to the cooling time by Cioffi & Shull (1991):

$$t_{cool} = 1.49 \cdot 10^4 \epsilon_0^{3/14} n_0^{-4/7} \zeta^{-5/14} \text{ yr} , \quad (1)$$

where $\zeta = Z/Z_\odot$, n_0 is the hydrogen number density, ϵ_0 is the energy released during a SN explosion in units of 10^{51} erg and we take always $\epsilon_0 = 1$. Old (Cox 1972, long dashed & dotted line) and new (Cioffi & Shull 1991) cooling times are compared in figure 1, where metallicity and density of the ISM evolve in a self-consistent way as a functions of time. The new cooling time (solid line) is about 3 times lower than the older one after 0.1 Gyr from the beginning of galactic evolution and that, soon after 0.2 Gyr, the metallicity becomes oversolar and makes the cooling ~ 10 times more efficient. The most important consequence is that, while in previous works flat initial mass functions (IMF) were preferred to get the right amount of elements in the ICM, now we show that models with Salpeter IMF as the best ones. The reason is that the faster the metallicity grows the more efficient the cooling is. So, if we compare a galaxy with a flat IMF ($x=0.95$) with a galaxy of the same initial mass with Salpeter IMF, the latter undergoes galactic wind earlier than the former and consequently eject more metals into the ICM.

The second fundamental hypothesis on energetics of the ISM is that SNe Ia are allowed to transfer all of their initial blast wave energy into the ISM:

$$\epsilon_{SNIa} = 1 . \quad (2)$$

In fact Recchi et al. (2001) showed that radiative losses for SNIa are negligible, since their explosions occur in a medium already heated by SNII. Therefore for SNe II, which explode first in a cold and dense medium, we allow for the cooling as described before. This results into an efficiency of energy transfer of no more than 3% per SNII. On the other hand for type Ia SNe, exploding only after at least 30-40 Myr, we assume an efficiency of energy transfer of 100%.

Among all the models we run, here we will present the results of the best ones:

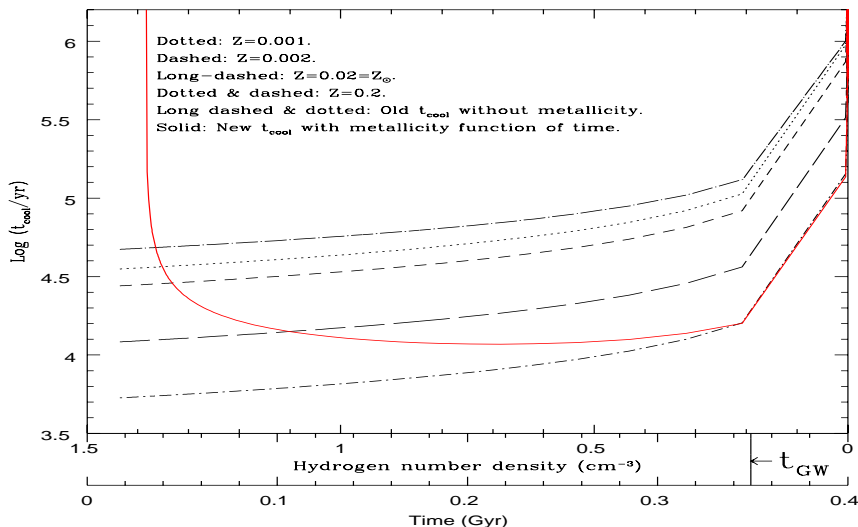


Figure 1. The comparison between different cooling times as a function of ISM density and metallicity. The new cooling time of Cioffi & Shull (1991) is shown by the solid line. The new cooling times at fixed Z are shown with dashed and dotted lines. The old cooling time independent of Z is indicated by the long dashed & dotted line.

Model MG : best model of Matteucci & Gibson (1995). It is a one-zone model with Arimoto & Yoshii (1987, AY) IMF, cooling time and SNR evolution by Cox (1972) and no morphological evolution of S0 galaxies allowed. We run it for comparison with our models with new energetic prescriptions.

Model I : one-zone model with Salpeter (1955) IMF, Cioffi & Shull (1991) cooling time, SNIa without cooling and morphological evolution of S0 galaxies allowed.

Model II : multi-zone model (see Martinelli et al. 2000 for details) with the same prescriptions of model I.

Despite of the hypothesis on type Ia SNR, the mean efficiency per SN (Ia+II) explosion is no more than $\sim 20\%$ for models I and II while it is $\sim 1.7\%$ for model MG. Another difference is that, thanks to the new prescriptions, the energy provided by SNIa makes galactic winds continuous out to the present time. Therefore models I and II release larger masses of elements and energy into the ICM than in the MG case.

3. Time evolution of Abundances and Energy

We consider galaxies in the range $10^9 - 2 \cdot 10^{12} M_\odot$ in order to find the parameters linking the luminous mass $M_l(z)$ of the galaxy and the masses of the chemical elements as well as the thermal energy $E_{th}(z)$ ejected into the ICM. In particular,

we obtain relations of the type:

$$E_{th}(z) = A(z) M_l^{\beta(z)}(z), \quad (3)$$

$$M_{el}(z) = B(z) M_l^{\delta(z)}(z), \quad (4)$$

where z is the redshift and A, B, β and δ are least-square fit parameters. For this choice of cosmological parameters $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we integrate relations (3) and (4) over the K-band Luminosity Function in clusters (LF), taking into account the LF evolution with redshift (while Martinelli et al. 2000 did not) and the possibility of morphological evolution for S0 galaxies into spirals for $z \geq 0.4$, for different cluster richness (n^*). In order to do this we take the LF at $z=0$ in the B-band from the observational data of Sandage et al. (1985), then we use the transformation from B-band to K-band by Fioc & Rocca-Volmerange (1999) and the evolutionary corrections from Poggianti (1997). We consider $M/L_K \sim 1$ at $z=0$ (e.g. Mobasher et al. 1999), and its evolution in time is calculated by means of the model of Jimenez et al. (1998). In order to compare model predictions with observed data we transform the cluster richness into temperature using the relation $kT \propto (n^*)^{0.8-1}$. The choice of the K luminosity is due to the fact that it does not vary dramatically with galaxy evolution as it is the case for B luminosity, which is very sensitive to young and massive stars.

4. Results and Conclusions

In Figure 2 we show the iron abundance (relative to the solar value) predicted by model II compared to data by White (2000). An AY IMF (solid line) can lead to a larger amount of Fe in the ICM than the observed value. We would have seen the same trend if we had used model I, since one and multi-zone models give quite similar results (as shown also by Table 1). Our models are in agreement also with $[\alpha/Fe]$, but we predict a slightly lower O abundance. As we can see from Table 1, SNe can provide $\sim 0.2-0.3$ keV per particle. From the chemical point of view, we show in Figure 3 the evolution of $[O/Fe]$ as a function of redshift and metallicity. At high redshift there is a fast decrease of O abundance due to the large production of Fe by SNIa, whereas there is no evidence of evolution for $z \leq 1$, in agreement with observations.

In summary, our conclusions are:

- In both one and multi-zone models, only those with Salpeter IMF reproduce the ICM Fe abundance as well as the observed $[Si/Fe]$ ratios.
- Best models can provide 0.2-0.3 keV per ICM particle with a mean SN efficiency of $\sim 20\%$.
- No relevant evolution is found for abundances and energy per particle from $z=0$ out to $z=1$, in agreement with observational data (e.g. Matsumoto et al. 2000).
- In both old and new models type Ia SNe play a fundamental role in providing energy ($\sim 80 - 95\%$) and Fe ($\sim 45 - 80\%$) to the ICM.

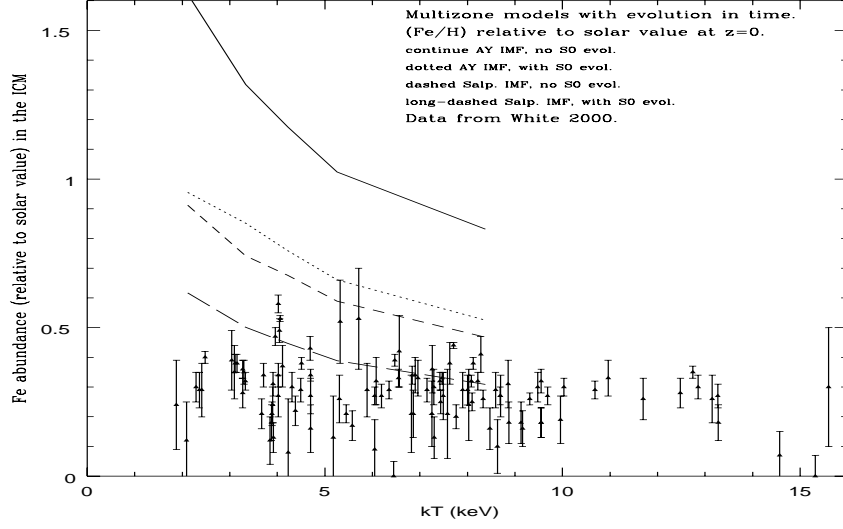


Figure 2. Fe abundances in the ICM as predicted by multizone model compared to the observed one by White (2000), as a function of cluster temperature.

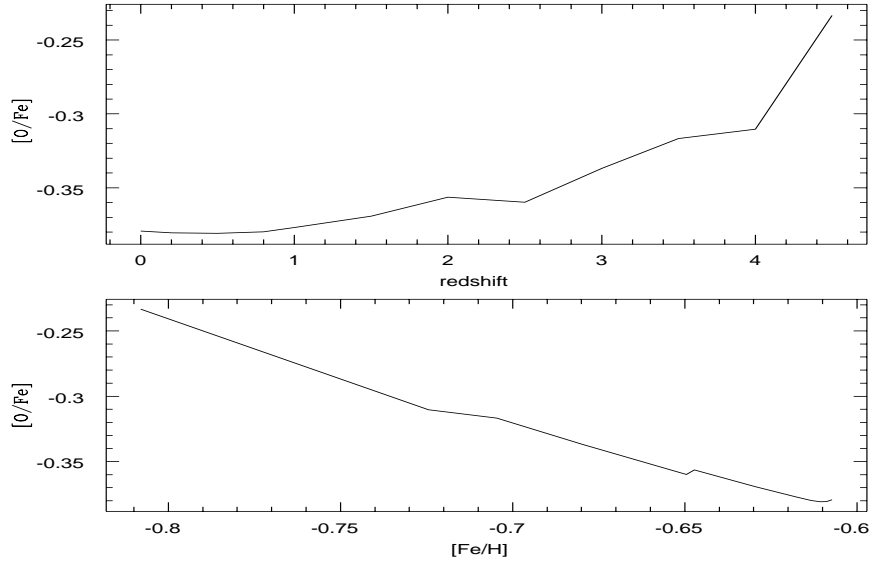


Figure 3. Evolution of $[O/Fe]$ versus redshift in Coma-like cluster.

Table 1. Abundances in the ICM and energy per ICM particle for best models with evolution in time for Coma and Virgo clusters.

Coma	[O/Fe] obs.	[Si/Fe] obs.	$\frac{Fe}{Fe_{\odot}}$ obs.		
	$< 0.01 \pm 0.14 >^*$	$0.51 \pm 0.60^{**}$ $< 0.14 \pm 0.10 >^*$	$< 0.23 >^{\dagger}$ $0.33 \pm 0.05^{\ddagger}$		
	[O/Fe]	[Si/Fe]	$\frac{Fe}{Fe_{\odot}}$	M_{gas}^{ej} $10^{13} M_{\odot}$	E_{pp} (keV)
MG	0.09	0.21	~ 0.31	1.27	0.19
I	-0.38	0.003	~ 0.24	0.32	0.13
II	-0.66	-0.08	~ 0.39	0.30	0.22
Virgo	[O/Fe] obs.	[Si/Fe] obs.	$\frac{Fe}{Fe_{\odot}}$ obs.		
	$< 0.01 \pm 0.14 >^*$	$0.16 \pm 0.18^{**}$ $< 0.14 \pm 0.10 >^*$	$0.40 \pm 0.02^{\P}$ $0.55 \pm 0.04^{\ddagger}$		
	[O/Fe]	[Si/Fe]	$\frac{Fe}{Fe_{\odot}}$	M_{gas}^{ej} $10^{13} M_{\odot}$	E_{pp} (keV)
MG	0.08	0.21	~ 0.50	0.51	0.30
I	-0.38	0.003	~ 0.35	0.13	0.21
II	-0.66	-0.08	~ 0.61	0.12	0.34

† (Fe/H)observed in Coma cluster from De Grandi & Molendi (2001, Beppo-Sax); ‡ by Matsumoto et al. (2000). ¶ (Fe/H)observed in Virgo cluster from White (2000, ASCA). ** [Si/Fe] from Fukazawa et al. (1998). * [Si/Fe], [O/Fe] weighted mean from Ishimaru & Arimoto (1997) for cluster A496, A1060, A2199 and AWM7. $M_{gas}^{ej} \sim 1 - 20\% M_{ICM}$.

- In spite of the large contribution from SNIa, SNe in general seem not to be able to provide the requested 1 keV per particle. We need perhaps other energy sources (e.g. quasars), although we might have underestimated the energy contribution from type II SNe.
- Chandra and XMM observations on abundances and abundance gradients in the ICM will set stronger constraints to our models.

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